MASS LOSS FROM LUMINOUS BLUE VARIABLES AND QUASI-PERIODIC MODULATIONS OF RADIO SUPERNOVAE

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RESUMEN

Favor de proporcionar un resumen en español. If you cannot provide a spanish abstract, the editors will do this. Massive stars, supernovae (SNe), and long-duration gamma-ray bursts (GRBs) have a huge impact on their environment. Despite their importance, a comprehensive knowledge of which massive stars produce which SN/GRB is hitherto lacking. We present a brief overview about our knowledge of mass loss in the Hertzsprung-Russell Diagram (HRD) covering evolutionary phases of the OB main sequence, the unstable Luminous Blue Variable (LBV) stage, and the Wolf-Rayet (WR) phase. Despite the fact that metals produced by "self-enrichment" in WR atmospheres exceed the initial – host galaxy – metallicity, by orders of magnitude, a particularly strong dependence of the mass-loss rate on the *initial* metallicity is found for WR stars at sub-solar metallicities (1/10 – 1/100 solar). This provides a significant boost to the collapsar model for GRBs, as it may present a viable mechanism to prevent the loss of angular momentum by stellar winds at low metallicity, whilst strong Galactic WR winds may inhibit GRBs occurring at solar metallicities. Furthermore, we discuss recently reported quasi-sinusoidal modulations in the radio lightcurves of SNe 2001ig and 2003bg. We show that both the sinusoidal behaviour and the recurrence timescale of these modulations are consistent with the predicted mass-loss behaviour of LBVs, and we suggest LBVs may be the progenitors of some core-collapse SNe.

ABSTRACT

Massive stars, supernovae (SNe), and long-duration gamma-ray bursts (GRBs) have a huge impact on their environment. Despite their importance, a comprehensive knowledge of which massive stars produce which SN/GRB is hitherto lacking. We present a brief overview about our knowledge of mass loss in the Hertzsprung-Russell Diagram (HRD) covering evolutionary phases of the OB main sequence, the unstable Luminous Blue Variable (LBV) stage, and the Wolf-Rayet (WR) phase. Despite the fact that metals produced by "self-enrichment" in WR atmospheres exceed the initial – host galaxy – metallicity, by orders of magnitude, a particularly strong dependence of the mass-loss rate on the *initial* metallicity is found for WR stars at sub-solar metallicities (1/10 – 1/100 solar). This provides a significant boost to the collapsar model for GRBs, as it may present a viable mechanism to prevent the loss of angular momentum by stellar winds at low metallicity, whilst strong Galactic WR winds may inhibit GRBs occurring at solar metallicities. Furthermore, we discuss recently reported quasi-sinusoidal modulations in the radio lightcurves of SNe 2001ig and 2003bg. We show that both the sinusoidal behaviour and the recurrence timescale of these modulations are consistent with the predicted mass-loss behaviour of LBVs, and we suggest LBVs may be the progenitors of some core-collapse SNe.

Key Words: **STARS: MASS LOSS — STARS: STELLAR WINDS — STARS: WOLF-RAYET — STARS: LUMINOUS BLUE VARIABLE — SUPERNOVAE**

1. INTRODUCTION

Massive star winds and core-collapse supernovae (SNe) have a huge influence on their environments by driving the chemical evolution of galaxies and shaping the interstellar medium over all cosmological epochs, since the very first stars came into existence. Despite their importance, the lives and deaths of massive stars are poorly understood. Despite theoretical progress (e.g. Hirschi et al. 2004), it is not known with any degree of certainty which massive stars produce which SNe/GRB.

While progress is being made in the direct identification of SN progenitors by searching for these in pre-explosion images (e.g. Smartt 2002; van Dyk et al. 2003), current progenitor masses appear to be limited to stellar masses not significantly

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greater than $\sim$10-15$M_\odot$, likely as a result of the initial mass function.

The evolution of more massive stars (M > 40 $M_\odot$) is largely unconstrained, but it is generally accepted that mass loss drives these objects through the O star, Luminous Blue Variable (LBV), and Wolf-Rayet (WR) phases (e.g. Chiosi & Maeder 1986). Mass loss also determines the stellar mass before collapse, and is therefore relevant for the type of compact remnant that is left behind (i.e. neutron star or black hole). This process is expected to depend on the metal content (Z) of the host galaxy (e.g. Eldridge & Vink 2006). As WR stars are the likely progenitors of long-duration GRBs (Woosley 1993), the strength of WR winds as a function of Z is especially relevant for setting the threshold Z for forming GRBs.

Furthermore, massive stars explode in environments that have been modified by mass loss from the progenitor. The SN ejecta interact first with this circumstellar material before interacting with interstellar material. We might therefore expect that the different wind properties over the lifespan of a massive star be imprinted onto the resulting circumstellar media (CSM), and we would expect these differences to be seen in the interaction between the SN ejecta and surrounding material. By quantifying these differences one may be able to constrain the evolutionary phase of the exploding object.

Over the last decades, radio observations of SNe have provided a means with which to constrain the density of the CSM around core-collapse SNe. The inferred mass-loss rates from modelling of most radio SN light curves yield values of $\dot{M}$ $\sim$$10^{-6}$ – $10^{-4} M_\odot \mathrm{yr}^{-1}$ (e.g. compilation in Weiler et al. 2002). Unfortunately, these average mass-loss rates are generally only accurate to within a factor of $\sim$10, and are typical of almost all types of massive star, making it difficult to pin down the evolutionary phase during which core-collapse occurred.

However, a small subset of radio SNe show quasi-periodic modulations in their radio lightcurves. We argue that this type of modulation may be the result of an LBV that underwent S Doradus variations which entailed opacity changes in the wind-driving region, resulting in varying mass-loss rates (Vink & de Koter 2002; Kotak & Vink 2006).

Given the crucial role that mass loss plays for massive star evolution, we briefly discuss recent mass-loss predictions in order of decreasing temperature: WR stars → OB supergiants → LBVs (Sects. 2 - 4). In Sects. 5 and 6, we link our knowledge of mass loss to certain types of radio SNe, and discuss whether LBVs may explode in Sect. 7.

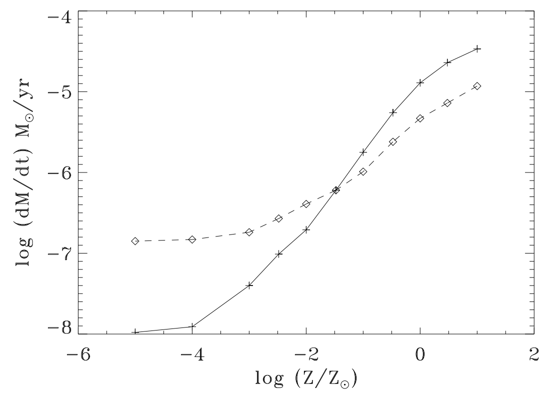

Fig. 1. Mass loss versus initial Z for late-type nitrogen-rich (WN) stars (solid line) and carbon-rich WC stars (dashed line). Note that metal self-enrichment is accounted for, but does not enter in our expression of Z. See Vink & de Koter (2005) for details.

2. WOLF-RAYET MASS-LOSS RATES AS A FUNCTION OF METAL CONTENT

In recent years, it has become clear that long-duration gamma-ray bursts (GRBs) are associated with the explosion of a massive star, providing impetus to the collapsar model (MacFadyen & Woosley 1999). The model works best if the progenitor fulfils the following two criteria: (i) the absence of a thick hydrogen envelope (enabling the jet to emerge), and (ii) rapid rotation of the core (allowing a disk to form). This may point towards a rapidly rotating WR star.

WR stars are believed to be the result of mass-loss during earlier evolutionary phases (the "Conti" scenario (Conti 1976)), while in a complementary scenario, the removal of the thick hydrogen envelope may be due to a companion. Recently, an alternative scenario for producing a GRB progenitor has gained popularity (Yoon & Langer 2005; Woosley & Heger 2006): when a star rotates rapidly, it may mix "quasi homogeneously", and the object may not develop the classical core-envelope structure, but remain small. A potential problem for producing a GRB in this scenario is that Galactic WR stars have strong stellar winds which may remove the angular momentum (Langer 1998), making it challenging to produce a GRB.

This problem might be overcome if WR winds are weaker at low Z, so the question is: "are the winds of WR stars Z-dependent?" and if so, "how strong is this dependence?" The dense winds of WR stars are

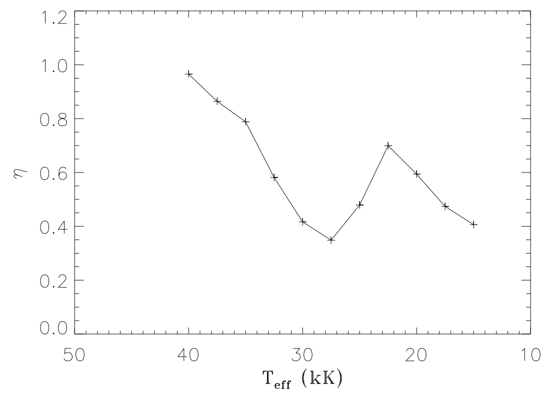

Fig. 2. Wind efficiency $\eta = (\dot{M} v_\infty)/(L_*/c)$ as a function of effective temperature. The predictions are taken from Vink et al. (2000). Note the presence of the bi-stability jump around 25 kK, where η increases as Fe recombines to Fe III.

likely driven by radiation pressure (Nugis & Lamers 2002; Gräfener & Hamann 2005), just like their less extreme O star counterparts.

This need not imply that WR winds depend on metal content, as WR stars produce copious amounts of metals such as carbon (in WC stars). If, on the one hand, these self-enriched elements dominate the driving (by their sheer number of particles), one would expect WR winds to be independent of their initial Z and the requirements of the collapsar model may never be met. If, on the other hand, iron (Fe) is predominantly responsible for the driving (as in O stars; Vink et al. 2001), WR winds might indeed be less efficient in low Z galaxies.

To address this issue regarding the Z-dependence of WR winds, (Vink & de Koter 2005) computed mass-loss rates for late-type WN and WC stars as a function of the initial metal content (representative of the host galaxy Z). The results are shown in Fig. 1. For a discussion of the flattening in the mass-loss-Z dependence for initial metallicities below log $(Z/Z_\odot) = -2$ and potential consequences for the first stars (Pop III), the reader is referred to Vink (2006), but for the Z range down to log $(Z/Z_\odot) = -2$, the mass loss is found to drop steeply, as $\dot{M} \propto Z^{0.85}$, for the WN phase - where WR stars spend most of their time. This inefficiency of WR mass loss at subsolar Z may prevent the loss of stellar angular momentum, and may provide a boost to the collapsar model.

3. MASS LOSS FROM OB STARS: ABSOLUTE RATES AND THE BI-STABILITY JUMP

We now switch from a discussion of Z-dependent mass loss to one of $T_{\rm eff}$-dependent mass loss. We describe the expected wind properties in terms of their wind efficiency number $\eta = (\dot{M} v_\infty)/(L_*/c)$, a measure for the momentum transfer from the photons to the ions in the wind. Vink et al. (2000) computed wind models as a function of effective temperature (Fig. 2). The overall behaviour is one of decreasing η with decreasing $T_{\rm eff}$ due to a growing mismatch between the wavelengths of the maximum opacity (in the UV) and the flux (gradually moving towards longer wavelengths). The behaviour changes at the "bi-stability jump" (BSJ; e.g. Lamers et al. 1995), where η *increases* by a factor of 2-3, as Fe IV recombines to Fe III (Vink et al. 1999).

Recent mass-loss studies (Trundle & Lennon 2005; Crowther et al. 2006) have reconfirmed discrepancies between empirical mass-loss rates and predictions for B supergiants (Vink et al. 2000). Discrepancies have also been reported for O stars (Bouret et al. 2003; Fullerton et al. 2006), and it is as yet unclear whether the reported discrepancies for B supergiants are due to model assumptions (e.g. the neglect of wind clumping) or the physical reality of the BSJ. The most accurate way to derive $\dot{M}$ is believed to be through radio observations. Intriguingly, Benaglia et al. (2007) present empirical radio mass-loss rates as a function of effective temperature that resemble the mass-loss efficiency behaviour predicted by Vink et al. (2000). This may well be the first evidence of the presence of a mass-loss BSJ at the boundary between O and B supergiants. The relevance for stellar evolution is that when massive stars evolve at constant luminosity towards lower $T_{\rm eff}$, they are anticipated to cross the BSJ. Interestingly, LBVs brighter than log $(L/L_\odot) = 5.8$ (see Fig. 3). are expected to encounter it continuously - on timescales of their photometric S Doradus variability, discussed in the next section.

4. MASS LOSS FROM LUMINOUS BLUE VARIABLES

LBVs are unstable massive stars in the upper part of the HRD (e.g. Humphreys & Davidson 1994). As can be seen in Fig. 3, the "classical" LBVs, like AG Car, are anticipated to cross the BSJ at $\sim$ 21 000 K. One of the defining characteristics for LBVs is their S Doradus (SD) variation of $\sim$1 – 2 mag on timescales of years (short SD phases) to decades (long SD phases) (van Genderen 2001). Vink & de Koter (2002) computed LBV mass-loss rates as a function of $T_{\rm eff}$- shown in Fig. 4. Overplotted are the empirical Hα mass-loss rates for AG Car (Stahl et al. 2001), which vary on the timescales of the photometric S Doradus variability. Although

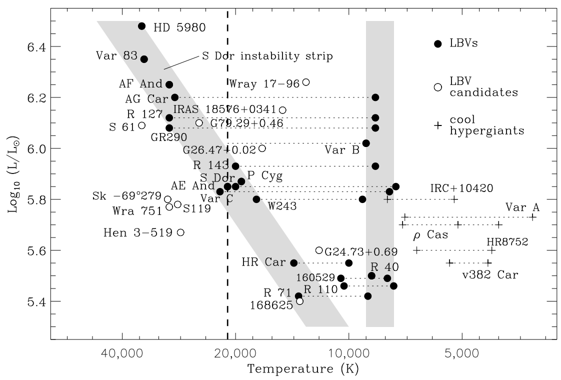

Fig. 3. The LBVs in the HRD. The shaded areas represent the S Doradus instability strip (diagonal) and the position of the LBVs during outburst (vertical). The dashed vertical line at 21 000 K indicates the position of the bi-stability jump. The figure is taken from Smith et al. (2004).

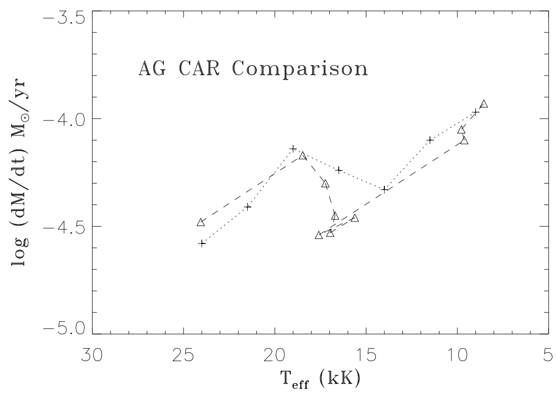

Fig. 4. Predicted (dotted line) and empirical (dashed line) mass-loss rates versus $T_{\rm eff}$ for the LBV AG Car. Note that both the qualitative behaviour and the amplitude of the mass-loss variations are well reproduced. See Vink & de Koter (2002) for details.

the agreement is not perfect (see Vink & de Koter (2002) for a discussion), the amplitude of the predicted variability fits the observations well, and most importantly the overall behaviour appears to be very similar, and may indeed be explained in terms of the physics of the BSJ. This bi-stable behaviour in an individual stellar wind (Pauldrach & Puls 1990) causes the star to flip back and forth between two states: that of a low mass loss, high-velocity wind, to a high mass-loss, low velocity wind. The wind density ($\propto \dot{M}/v_\infty$) would therefore be expected to change by a factor of $\sim$2 $\times$ $\sim$2, i.e. $\sim$4 on the timescale of the SD variations. In the absence of any other material around the star, this would result in a pattern of concentric shells of varying density.

5. RADIO SUPERNOVAE AND PROGENITOR MASS LOSS

Radio SNe (RSNe) lightcurves and the model for SN interaction with the surrounding circumstellar material has been reviewed by Weiler et al. (1986). The radio emission is due to non-thermal electrons, while the absorption may be due to both synchrotron self absorption as well as free-free absorption (Chevalier 1982; Fransson & Björnsson 1998). Examples of the rise, peak, and power-law decline of radio lightcurves are shown in Fig. 5. (The episodic bumps at late time are discussed in Sect. 6)

The model constrains the wind density and thus the ratio of $\dot{M}$ to the terminal wind velocity (v_∞): $\rho \propto \dot{M}/v_\infty r^2$. Assuming v_∞, Weiler et al. (2002) list $\dot{M}$ values in the range 10^{-6}–10^{-4} $M_\odot {\rm yr}^{-1}$. Fortunately, these values agree with mass-loss predictions, but are broadly representative for massive stars over almost all post-main sequence evolutionary phases, making it hard to infer the progenitor from radio lightcurves alone, unless these lightcurves betray their progenitor in some another way.

6. QUASI-PERIODIC OSCILLATIONS IN RADIO SNE LIGHTCURVES

A number of recent RSNe have shown sinusoidal modulations in their radio lightcurves, in particular SN 2001ig (Ryder et al. 2004) and SN 2003bg (Soderberg et al. 2006) are strikingly similar in terms of both amplitude and variability timescale (see Fig. 5). The recurrence timescale t of the bumps is $\sim$ 150 days. Using Eq. (13) from (Weiler et al. 1986):

$$\Delta P \ = \ \frac{R_{\rm shell}}{v_{\rm wind}} \ = \ \frac{v_{\rm ejecta}\ t_{\rm i}}{v_{\rm wind}\ m} \left(\frac{t}{t_{\rm i}}\right)^m \qquad (1)$$

where m is the deceleration parameter (here m = 0.85) and $t_{\rm i}$ is the time of measurement of the ejecta velocity relative to the moment of the explosion. Assuming $v_{\rm wind}$ = 10–20 km sec^{-1}, typical wind velocities for red (super)giants, (Ryder et al. 2004) found a period P between successive mass-loss phases that was too long for red (super)giant pulsations (100s of days, see however Heger et al. (1997)), but too short for thermal pulses (10^2–10^3 years). They therefore invoked an edge-on, eccentric binary scenario involving a WR-star and a massive companion. One of the main differences between LBV and red giant winds is that LBV winds are about 10 times faster. If the progenitor of SN 2001ig were an LBV, the expected period between successive mass-loss episodes would be $\Delta P \sim 25\,{\rm yr}$ (for an assumed

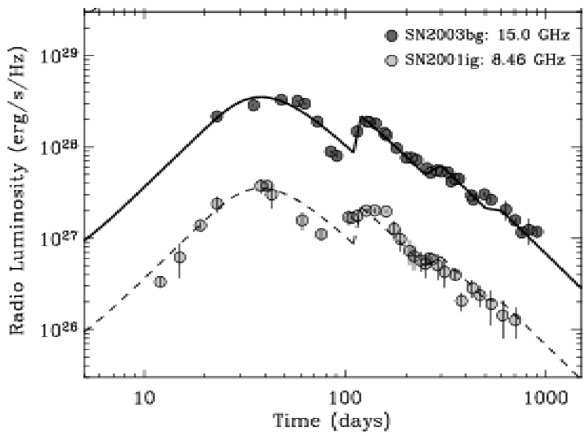

Fig. 5. Radio luminosity versus time for two strikingly similar recent SNe: 2001ig and 2003bg. Note the quasi-sinusoidal modulations during the power-law decline phase. Taken from Soderberg et al. (2006).

$v_{\rm wind} = 200\,{\rm km\,sec^{-1}}$), consistent with the long SD phase (Kotak & Vink 2006).

Soderberg et al. (2006) infer density enhancements of a factor of ~ 2 during the deviations from pure power-law evolution. They consider a range of options that might account for the modulations, but they favour a single-star progenitor model of a WR star that underwent episodes of intensified mass loss. However, they do not specify the physical mechanism that gives rise to these periods of enhanced mass loss. Our SD mechanism for LBVs may alleviate this shortcoming.

7. DISCUSSION: DO LBVS EXPLODE?

Are LBVs viable SNe progenitors? It may be relevant that both SNe 2001ig and 2003bg are "transitional" objects. SN 2001ig was initially classified as type II (showing H lines) but metamorphosed into a type Ib/c object (no H lines, weak He lines) about 9 months later. This suggests that it has lost most of its H-rich envelope. SN 2003bg however was first classified as a type Ic, but within a month the spectrum evolved into a type II SN. This transitional behaviour hints at the fact that their progenitors are intermediate evolutionary objects: H-rich compared to OB/red (super)giants, but H-poor compared to WR stars. LBVs are likely candidates.

Recently there has been much discussion regarding clumping in the winds of O stars. The value for the clumping factor is very much an open issue. Mokiem et al. (2007) show that if the empirical Hα rates are overestimated by a factor of two due to clumping, these empirical rates are in good agreement with the mass-loss predictions of Vink et al. (2000, 2001), and consequently our current knowledge of massive star evolution is not anticipated to be affected by clumped winds. If however the wind clumping factor would be *significantly* larger than a factor two/three (as has been suggested by UV analyses), this could have severe implications for massive star evolution. One consequence might be that giant LBV eruptions (η Car type eruptions, not the typifying SD variations) dominate the integrated mass loss during evolution (Smith & Owocki 2006). An alternative scenario could be that post-main sequence stars do not become WR stars, but explode early – during their LBV phase.

Here, we have presented indications that at least those SNe that show quasi-periodic modulations in their radio lightcurves might have LBV progenitors (Kotak & Vink 2006). It has also been speculated that LBVs may be the generic progenitors of type IIn SNe (Gal-Yam et al. 2006), however it may be more relevant to discuss IIn SNe as a "phenomenon" describing SN ejecta expanding into a dense CSM than a one-to-one correlation to a particular progenitor (Kotak et al. 2004). Nevertheless, some fraction of type IIn SNe may well have LBV progenitors although the observational evidence remains elusive.

It is relevant to note that the LBV candidate HD168625 is embedded in a bipolar-shaped nebula that resembles the triple-ring system around SN1987A. This similarity could hint that the progenitor of 1987A (i.e. the blue supergiant Sk-69 202) underwent an LBV giant eruption before it exploded (Smith 2007).

Future mass-loss predictions are anticipated to play an important role in obtaining knowledge about the lives and deaths of massive stars.

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